

# Testing of SLA-561V in NASA-Ames' Turbulent Flow Duct With Augmented Radiative Heating

Extended Abstract

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**As part of Mars Science Laboratory's (MSL) heatshield development program, SLA-561 was tested in NASA Ames Turbulent Flow Duct (TFD) Facility. For these tests, the TFD facility was modified to include a ceramic plate located in the wall opposite to the test model. Normally the TFD wall opposite to the test model is water-cooled steel. Installing a non-cooled ceramic plate allows the ceramic to absorb convective heating and radiate the energy back to the test model as the plate heats up. This work was an effort to increase the severity of TFD test conditions. Presented here are the results from these tests.**

## I. Introduction

**M**SL is scheduled for launch in the fall of 2011. The entry vehicle is designed to land the largest and heaviest payload of any Mars mission to date. As such, an unprecedented heatshield diameter of 4.5 meters is required to protect the vehicle during passage through the Martian atmosphere. The combination of large size and high ballistic coefficient ( $\sim 140 \text{ kg/m}^2$ ) will subject the PICA ablative heatshield to extensive turbulent boundary layer heating. Testing was conducted in the NASA Ames Turbulent Flow Duct Facility (TFD) to study the effects of turbulent flow heating in a high shear environment.

## II. Facility Description and Test Conditions

The TFD is a supersonic blow-down wind tunnel that uses an electric arc to heat the test gas, in this case air, and which can operate for several minutes. The test section is 22.9 cm wide and 5 cm high (see Fig. 1). The bulk enthalpy of the stream was  $\sim 8.8 \text{ MJ/kg}$  for the present test. The arc-heated air is expanded into the test chamber through a two-dimensional nozzle and reached a stream Mach number of 2.5 and a static pressure of about 0.1 atm. The test chamber is a water-cooled rectangular structure. The test specimen is a flush-mounted flat panel that forms one wall of the test section; the opposite wall was modified to have a ceramic plate inserted into the wall. Normally this wall is water-cooled. As the ceramic plates heats up, it is able to radiate energy back to the test model since the gas is optically thin.

Because the model is in a fixed position in the test section, it is exposed to the flow startup transient that lasts about 30-40% of the total run time, as will be shown subsequently. During steady-state conditions in the facility, the arc current was 2400 amps, and the reservoir chamber pressure was about 940 kPa.

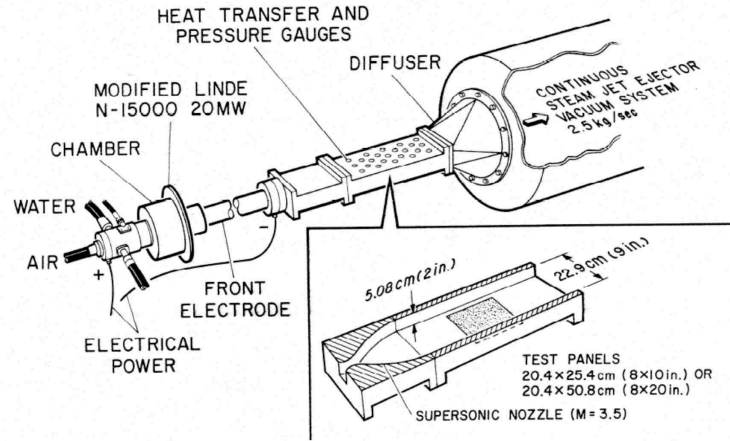
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## AMES 2×9 in. TURBULENT FLOW DUCT FACILITY

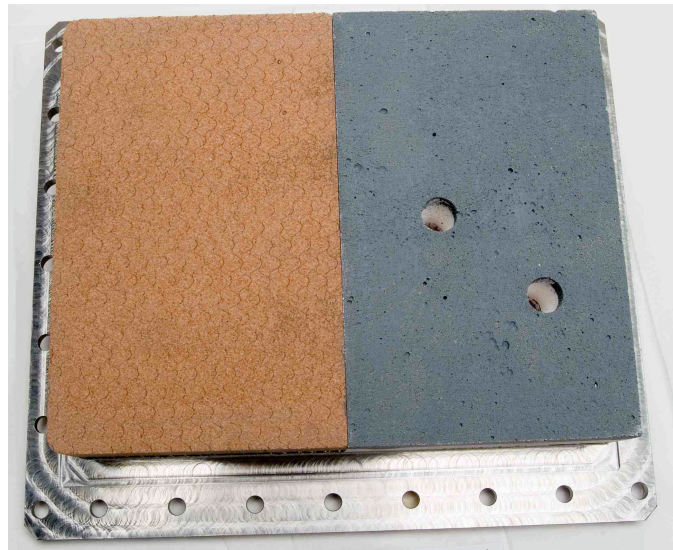


**Figure 1. TFD test model drawing**

### III. Model and Instrumentation

#### A. Test Model

The typical test model was fabricated with SLA-561V on the first half (left hand side) and Silfrax on the second (right hand side). The flow direction is from left to right. The Silfrax portion of the model in Figure 2 contains two ports. The one nearest the center of the model housed a Gardon gage calorimeter, while the one downstream and below center housed a radiometer.



**Figure 2. Pre-test photograph of a typical model. Flow direction is from left to right.**

The typical material stackup of the SLA-561V portion of the model is given in Figure 3. The model was made up of 2.54 cm (1 inch) thick SLA-561V and attached to a 1.3716 cm (0.54 inch) composite consisting of aluminum honeycomb and faceplate with stiffener M55J. The model was then attached to a 0.635 cm (0.25 inch) block of LI-2200 to act as non-conducting, adiabatic back wall. Finally this full assembly was then attached to the TFD wall by means of a steel model plate and steel retainer plate (Figure 4).

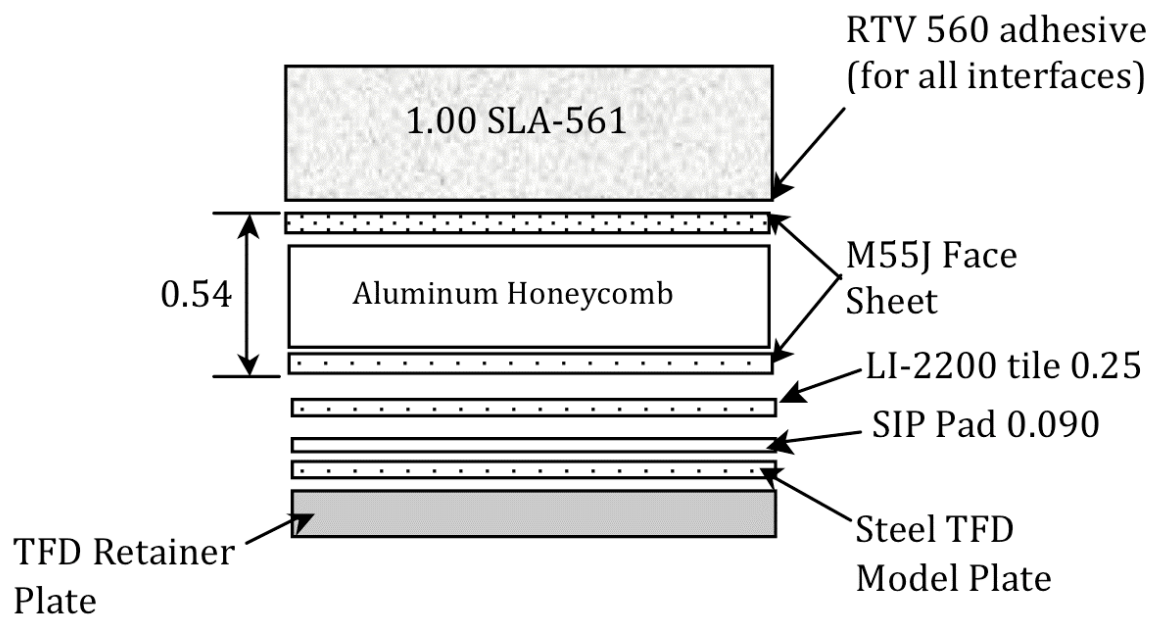


Figure 3. Schematic diagram of typical material stackup that included SLA-561V

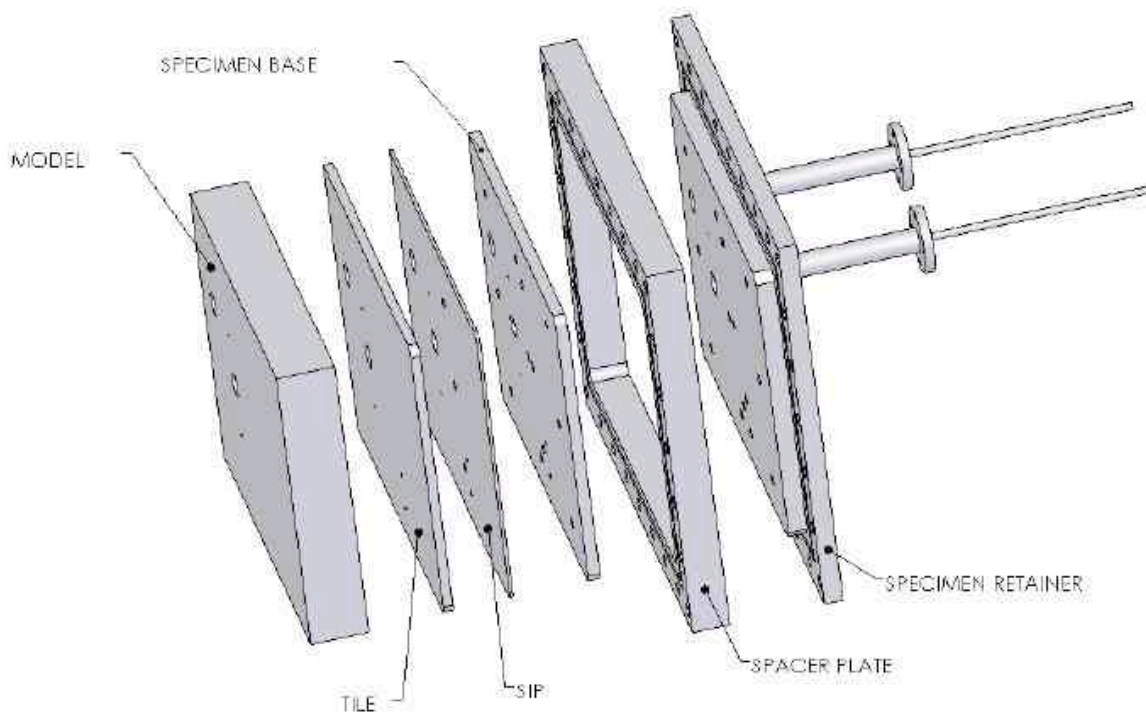
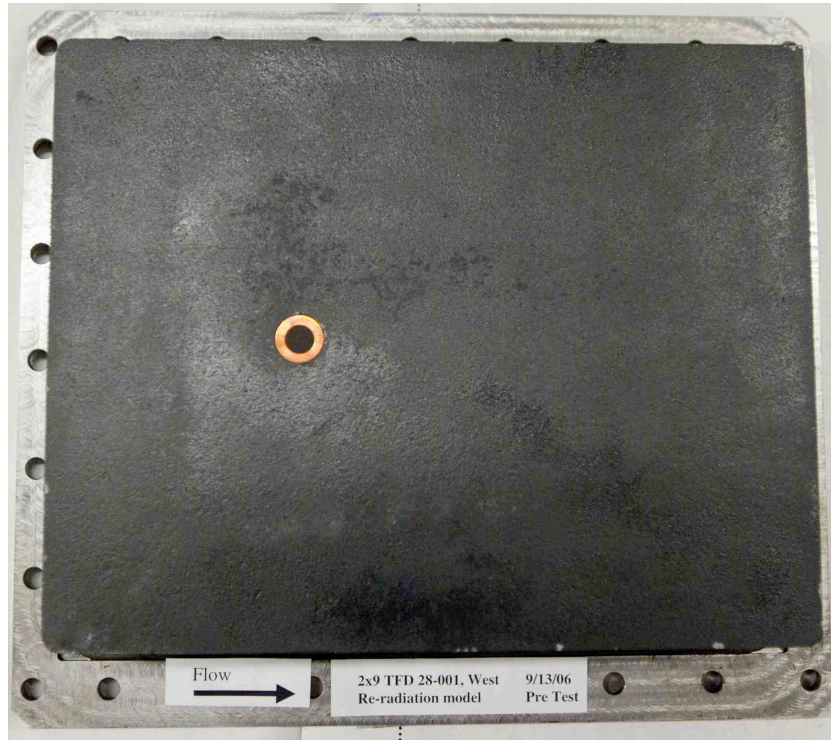


Figure 4. Typical model to TFD wall assembly

## B. Radiation Plate

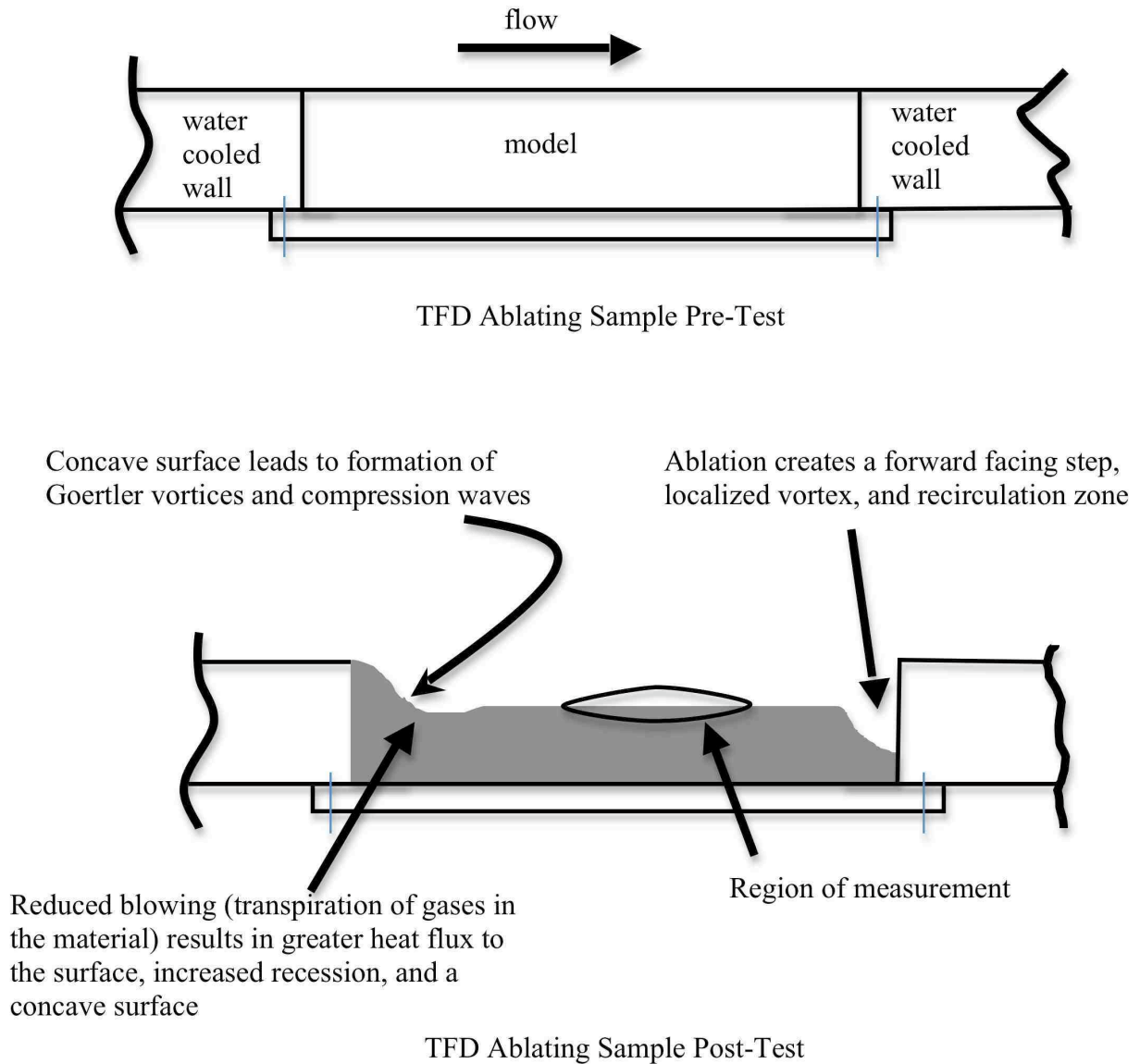
The radiation plate consisted of LI-2200 coated with TUF1. A photograph of the plate is given in Figure 5. The flow direction is from left to right. Located 8.255 cm (3.25 inches) from the leading edge of the plate is a pyrometer port, which was used to measure surface temperatures of the test model's SLA-561V during a test run. The same radiation plate was used for all test runs.



**Figure 5. Radiation plate model**

## IV. Background Theory - Typical ablator response in TFD

Before proceeding into experimental results, it is best to review typical results when testing an ablating model in the TFD. Shown in Figure 6 is a diagram of a typical pre-test and post-test ablating model. As noted in the figure, the junction between the water-cooled TFD walls and the model provides localized cooling due to in-depth lateral conduction at the edges of the model. This cooling reduces pyrolysis gas blowing, and blowing (or transpiration) is important at the boundary layer because it acts to reduce the localized convective heat rate. Near the leading edge, increases in localized heating due to reduced blowing leads to the formation of a steep concave surface. This concave surface leads to the formation of Göertler vortices and shock waves. Finally, at the trailing edge wall interface, ablation creates a forward-facing step. In this pocket is a localized vortex and recirculation zone.



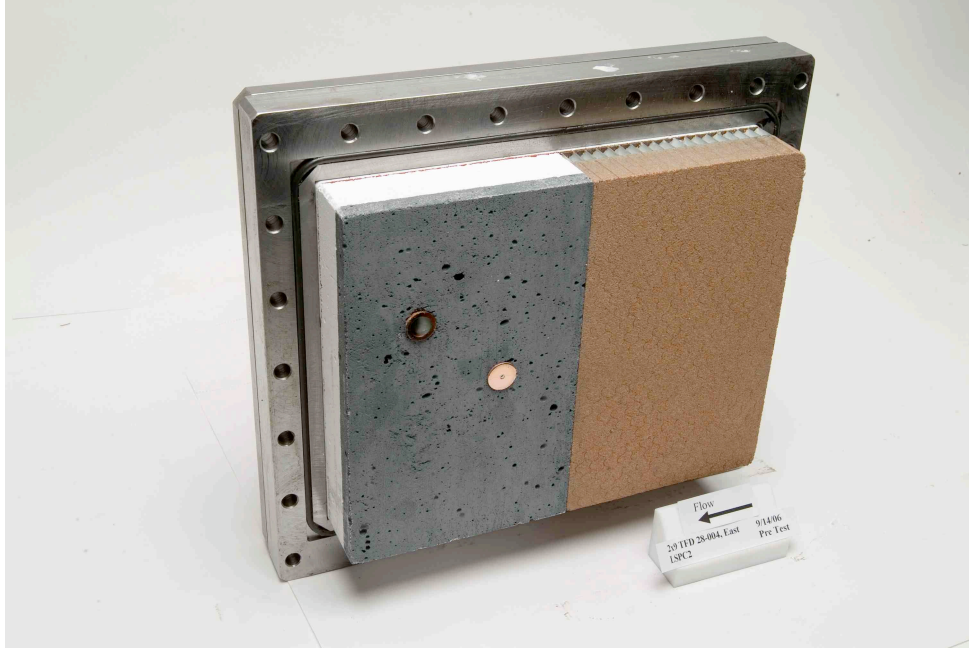
**Figure 6. Diagram illustrating typical ablator response in TFD**

## V. Results From Test Runs

### A. Photographs of the models

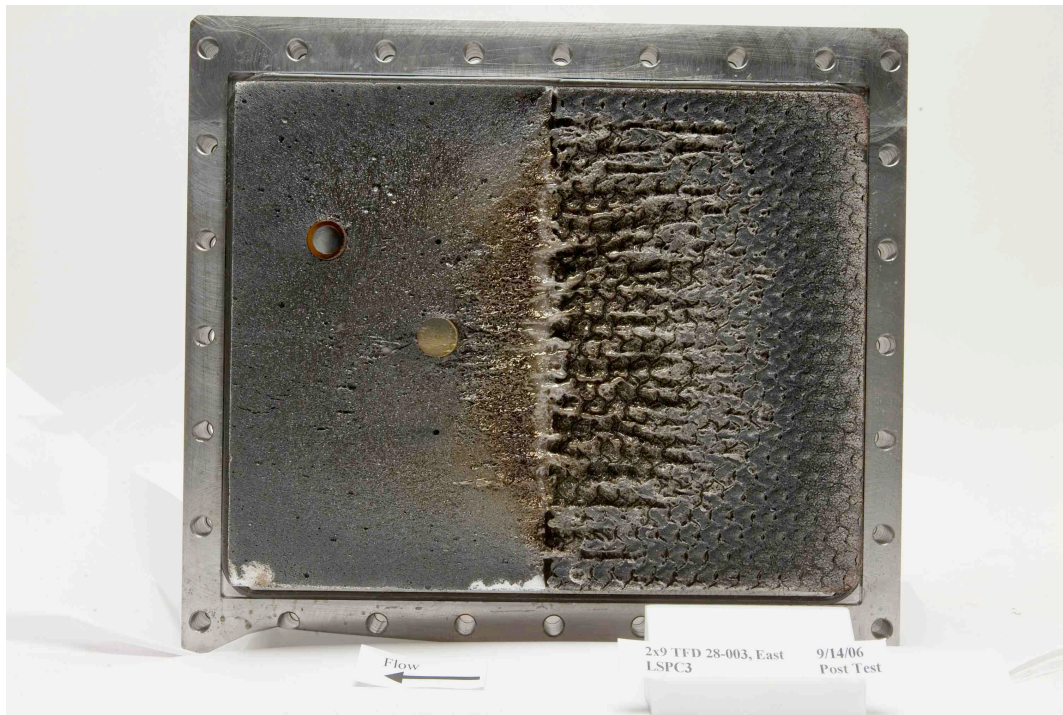
For tests at maximum TFD settings, only two models were tested. Shown in Figure 7 is a typical model prior to testing. The flow direction is from right to left. As shown in the figure, the gardon gage calorimeter had been cleaned prior to each run, but the radiometer had been damaged and was non-operational.





**Figure 7. Typical test model prior to testing. Gardon gage calorimeter had been cleaned prior to testing. Radiometer was damaged and non-operational prior to testing.**

Shown in Figure 8 is a top view, post-test photograph of the first model tested. The flow direction is from right to left. From this photograph it is evident that a great deal of glass melt flow from the SLA-561V had accumulated at the SLA-561/Silfrax interface. Also of note are the formation of Göertler vortices running stream-wise along the length of SLA.



**Figure 8. Post-test photograph of first model to be tested.**

Shown in Figure 9 is a side view, post-test photograph of the first model tested. The flow direction is from right to left. From this photograph it is evident that the char layer in the SLA-561V was well-defined. Also visible are the Göertler vortices and melt flow of glass.

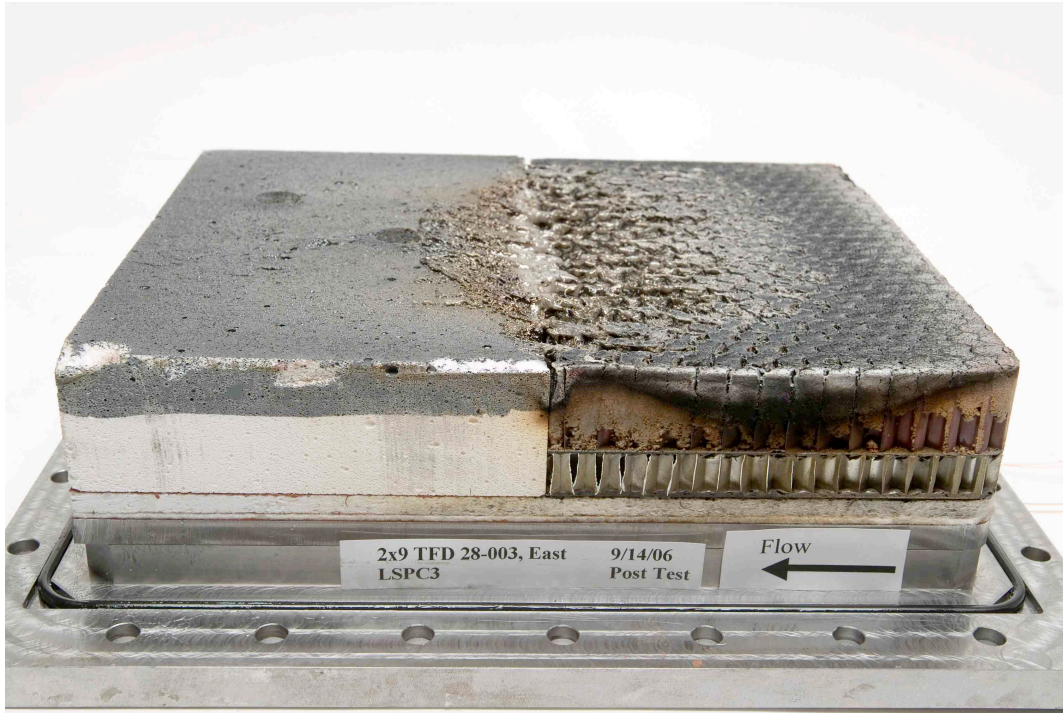


Figure 9. Post-test side view photograph of first model.

## B. Theory of TFD modifications

### 1. Radiative Heating Derived From Pyrometer Measurement

Radiative heating between two parallel plates ( $s_1$  and  $s_2$ ) where all of the radiation from one plate reaches the other is given by:

$$q_{rad} = \epsilon \sigma (T_{s_2}^4 - T_{s_1}^4) \quad (1)$$

where

$q_{rad}$  = radiative heat flux per unit area [ $\text{W}/\text{cm}^2$ ]

$\sigma$  = Stefan-Boltzmann constant [ $5.6703\text{E-}8 \text{ W}/\text{m}^2\text{K}^4$ ]

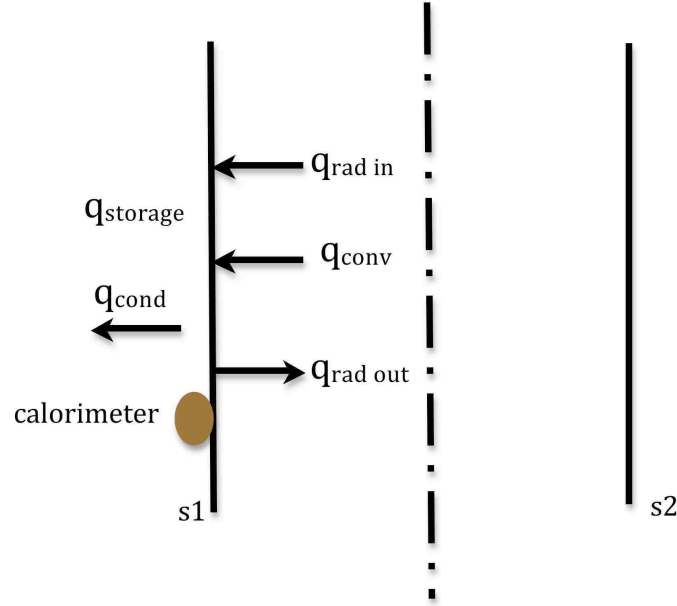
$T_x$  = surface temperature [K]

$\epsilon$  = emissivity of the radiating surface

The assumption that all of the radiation from each plate reaches the other is justified for two reasons: the gas between the plates is optically thin, and the plates (8" x 10") are spaced only 5.08 cm (2 in) apart. There will be some radiation lost to the water-cooled TFD walls, but this would be at highly oblique angles from the plate surface and would become significant only near the edges of the plates.

The energy terms at one plate are shown in Figure 10. Both plates,  $s_1$  and  $s_2$ , are not water-cooled. The emissivity of each plate should be similar: the Silfrax portion of the model and LI-2200 radiation plate were each TUF1 coated, but the SLA-561V was not. Based on this, a first order approximation would be that each wall receives identical convective heating and nearly identical radiative heating, and therefore should be nearly equal in surface temperature. If both plates were equal in temperature, equation 1 indicates that neither surface will emit nor absorb any radiant heating. What is lost, however, when comparing this arrangement to one where the opposite wall is water cooled, is that the cooled wall will absorb radiant heat from the model. This "cooling" mechanism is lost with

the current TFD configuration. As a result, net incident heating rates are similar to convection-only heating, but surface temperatures are allowed to rise significantly due to inability to radiantly “cool”. When testing SLA-561V under such conditions, increased surface temperatures lead to glass formation and melt flow.



**Figure 10. Energy balance of TFD walls**

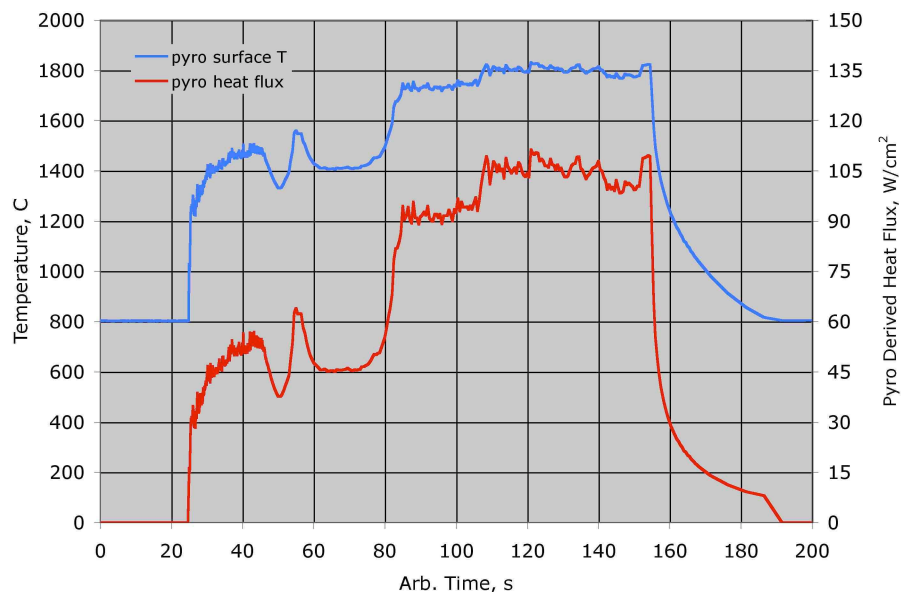
### C. Pyrometer measurements of SLA surface temperature

The temperature of the water-cooled calorimeter surface will be much less than the SLA-561V surface, which was  $\sim 1800^{\circ}\text{C}$  during the testing, (see Figure 11). Making the approximation that the charred SLA surface has an emissivity of one, leads to a simplified form of equation 1 to estimate the radiative heat flux emanating from the SLA surface.

$$q_{rad} = \sigma T_{SLA\ surface}^4 \quad (2)$$

Applying equation 2 to the pyrometer surface temperature readings leads to the inferred heat flux readings also given in Figure 11.

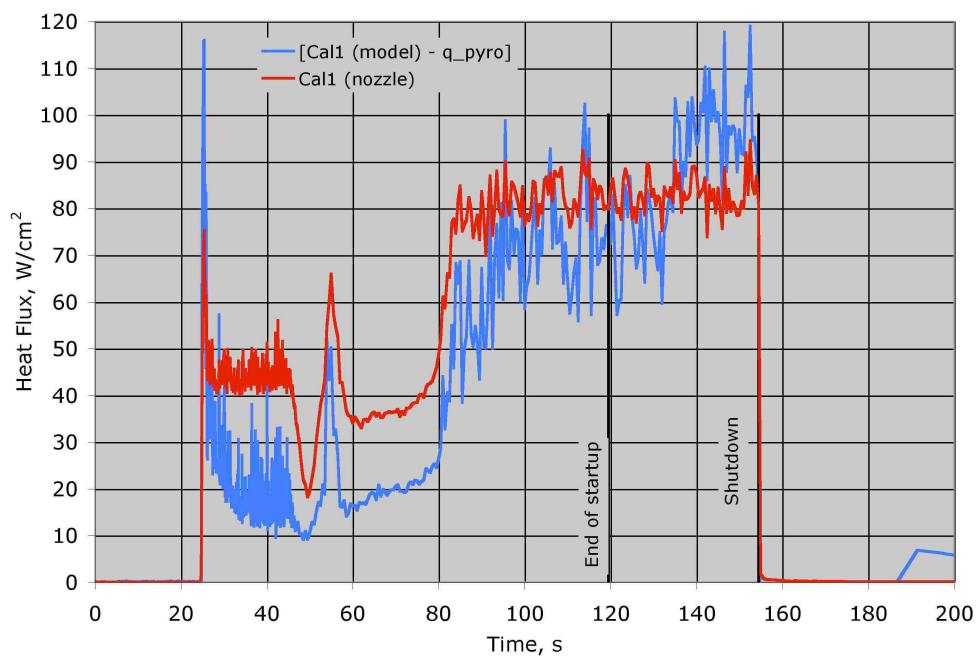




**Figure 11. Pyrometer readings of the second model tested**

Upstream of the TFD's nozzle exit at 7.4676 cm (2.94 inches) is a Gardon gage calorimeter, Cal1 (see Figure 12). Because of its location in the nozzle, this calorimeter is not exposed to radiative heat flux from the radiation plate, and as a result will only read convective heating of the flow. Its readings indicate a steady-state heat flux of approximately 80 W/cm<sup>2</sup>.

If the calorimeter in the model read the combined convective and incident radiation, then subtracting the pyrometer-derived radiative heat flux its readings should give values comparable to those found from C1. The results agree and are shown in Figure 12.



**Figure 12. Calorimeter comparison using pyrometer-derived heat flux for second model tested**

## **VI. Concluding Remarks**

The test that was conducted in the turbulent flow duct facility accomplished several objectives, although it was unable to simulate MSL peak conditions of heating rate and surface pressure. Most notably was the TFD facility modification, which allowed the test model surface temperature to increase substantially over the previous configuration. As such, the effects on SLA-561V were to see glass formation and melt flow. This was the first appearance of such a large amount of glass melt flow<sup>2</sup>, and as a result of these tests, further investigations of SLA-561V as a candidate heatshield material would be required. It should be emphasized, however, that the material did not experience any failure and that the char layer was well behaved.

## **Acknowledgments**

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## **References**